BREAKUP EFFECTS IN THE FUSION OF $^{6}Li + ^{90}Zr$ REACTION

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The dynamics of fusion reactions involving weakly bound nuclei had received impetus during last 20 years and is of astrophysical interest. The fusion dynamics of weakly bound/halo systems are quite different from that of the stable systems. For such systems, the fusion data in above barrier energy regions are significantly affected by the breakup channel. In above barrier energy regions, the fusion cross-sections are suppressed due to loss of fusion yields. The loosely bound system due to its low breakup threshold breaks up into two or more parts before reaching the interaction barrier and hence is partially absorbed by the target. This results in the loss of flux going into fusion channel and thus appeared as suppression of above barrier fusion cross-sections with reference to the outcomes of the coupled channel approach in the above barrier domain. The breakup threshold of loosely bound system plays a significant role in the fusion process and is expected to be related with the fusion suppression factors at above barrier energies [3-4].

The authors of Ref. [5] suggested that the below barrier fusion enhancement for the fusion of weakly bound system is due to involvement of the intrinsic degrees of freedom of the participants while the above barrier suppression of fusion cross-sections with respect to the coupled channel approach is originated due to breakup of weakly bound system in the entrance channel. In literature, the some experimental and theoretical evidences that showed fusion enhancement due to breakup channel while there were some reported literature which suggested fusion suppression due to involvement of the breakup channel of the weakly bound system [6]. The present work explores the fusion dynamics of $^{6}Li + ^{90}Zr$ reaction, wherein the projectile is weakly bound system and the target is stable system. The fusion dynamics of $^{6}Li + ^{90}Zr$ reaction is analyzed within the ground work of energy dependent Woods-Saxon potential (EDWSP) model [7-10] and the coupled channel approach [11]. In EDWSP model, the energy dependent interaction potential is used along with the one dimensional Wong formula [12]. The experimental data of $^{6}Li + ^{90}Zr$ reaction is measured by Kumawat et al., [13] and authors pointed that the above barrier fusion cross-section data of the chosen reaction is suppressed by a factor of 34% with respect to coupled channel calculations. In order to confirm such effects, the fusion dynamics of the studied system is analyzed in the present work. In the EDWSP model, the form of the static Woods-Saxon potential, which depends upon three ingredients: range, depth and diffuseness and is defined as

$$V_N(r) = \frac{-V_0}{\left[1+\exp\left(\frac{r-R_0}{a}\right)\right]}$$

where, V_0 is depth of nuclear potential, and 'a' is the diffuseness parameter of the nuclear potential. In the EDWSP model, the depth of Woods-Saxon potential is parameterized by the following relation.

$$V_0 = \left[A_P^{\frac{2}{3}} + A_T^{\frac{2}{3}} - (A_P + A_T)^{\frac{2}{3}}\right]\left[2.38 + 6.8(1+I_P+I_T)\frac{A_P^{\frac{1}{3}}A_T^{\frac{1}{3}}}{\left(A_P^{\frac{1}{3}}+A_T^{\frac{1}{3}}\right)}\right] MeV$$

where $I_P = \left(\frac{N_P - Z_P}{A_P}\right)$ and $I_T = \left(\frac{N_T - Z_T}{A_T}\right)$ are the isospin asymmetry of the reacting pairs.

In EDWSP model, the diffuseness parameter $a(E)$ is taken as energy dependent and hence is defined as

$$a(E) = 0.85\left[1 + \frac{r_0}{13.75\left(A_P^{-\frac{1}{3}} + A_T^{-\frac{1}{3}}\right)\left(1+\exp\left(\frac{\frac{E_{c.m.}}{V_{B0}} - 0.96}{0.03}\right)\right)}\right] fm$$

$E_{c.m.}$ is the incident energy in center of mass frame, V_{B0} is height of the Coulomb barrier. The range parameter (r_0) is related with the geometry of the fusing partners via $R_0 = r_0\left(A_P^{1/3} + A_T^{1/3}\right)$.

The theoretical estimations of $^{6}Li + ^{90}Zr$ reaction in no coupling limit are substantially underestimated in the below barrier energy regions with reference to the fusion data while at above energies, the no coupling calculations overestimate the fusion data as evident from Fig.1. To address the sub-barrier fusion enhancement, the couplings to intrinsic degrees of freedom must be incorporated in the theoretical approach. The inclusion of vibrational excitations of target produces larger sub-barrier fusion enhancement but still unable to recover the experimental data in below barrier energy regions. The projectile (^{6}Li) is loosely bound system with a breakup threshold of 1.475 *MeV*. Kumawat et al., [13] by including the projectile breakup channel and inelastic excitations of the target explained the observed sub-barrier fusion enhancement of the studied system. However, authors pointed out that the above coupled channel calculation overestimates the above barrier fusion data by 34%. Such suppression effects were correlated with the breakup channel of the projectile due to its low breakup threshold.

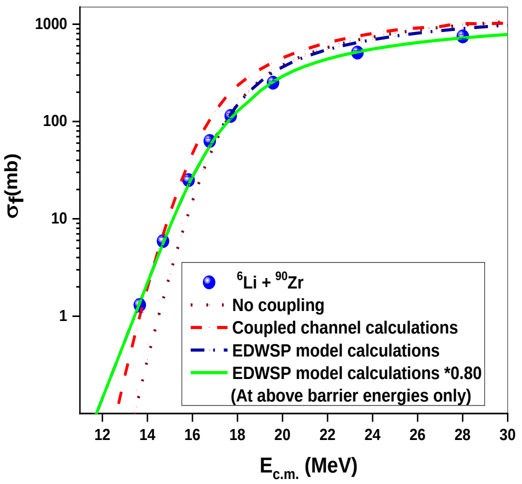

Fig.1. Fusion cross-sections of $^{6}Li+^{90}Zr$ reaction obtained by using the EDWSP model and the coupled channel approach and the theoretical calculations are compared with the available experimental data taken from Ref. [13].

However in the EDWSP model [7-10], the energy dependent character of nucleus-nucleus potential generates barrier lowering effects and also produces a spectrum of the energy dependent fusion barriers of different heights and weights. As a result, the fusion barriers having heights smaller than that of the uncoupled Coulomb barrier shift the incoming flux from elastic channel to fusion channel and subsequently predict larger fusion cross-sections at below barrier energies. As evident from Fig.1, the EDWSP outputs fairly reproduced the experimental data in the sub-barrier realm but the overestimate the above barrier fusion data. Although, the above barrier fusion data are suppressed with respect to the EDWSP calculations but the magnitude of the suppression factor is considerably smaller than that of the reported value. The EDWSP estimations at above barrier energies are suppressed by a factor of 20% which is much smaller than that of 34% as reported by the authors of Ref. [13]. Such suppression effects are due to breakup of projectile in the incoming channel before reaching the interaction barrier. The one or more breakup fragment of projectile is absorbed by the target while the remaining breakup fragment(s) continues in the beam direction.

In summary, the theoretical calculations based on the EDWP model and coupled channel model for $^{6}Li+^{90}Zr$ reaction clearly suggested the influences of the projectile breakup effects on the fusion process. Due to low breakup threshold, the projectile splits into two or more parts and hence is partially absorbed by the target. This ultimately results in the reduction of the incoming flux going into fusion channel and ultimately results in the suppression effects. The magnitude of fusion suppression effects at above barrier energies due to EDWSP model is considerable smaller than that of the reported value. As consequence of energy dependence in nucleus-nucleus potential, the EDWSP model produces barrier lowering mechanisms which in turn appropriately address the observed sub-barrier fusion anomalies of the studied system.

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